Current Progress on the Design and Analysis of the JWST ISIM Bonded Joints for Survivability at Cryogenic Temperatures

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JWST/ISIM Stress Team

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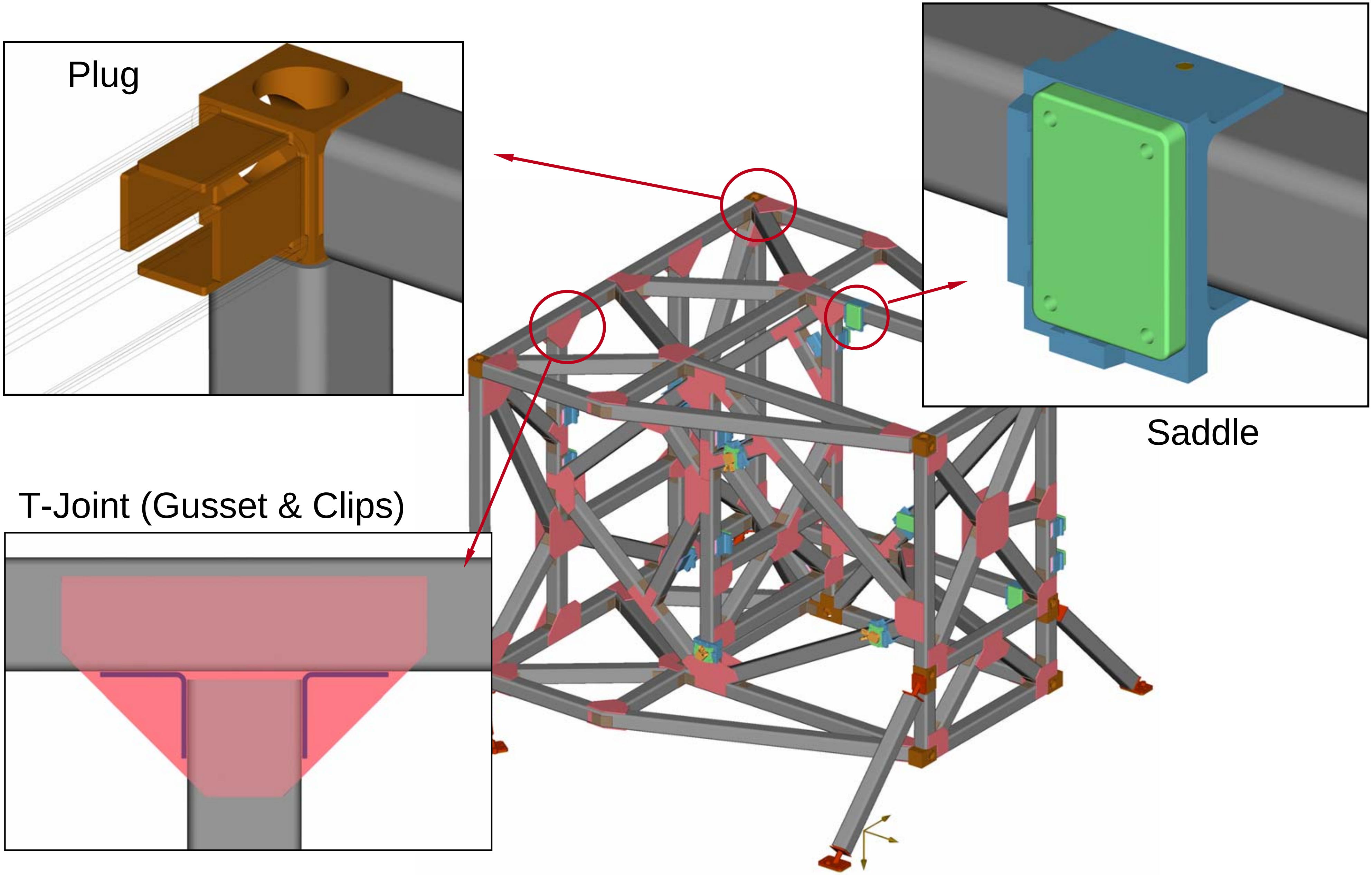
Design and Analysis Challenges

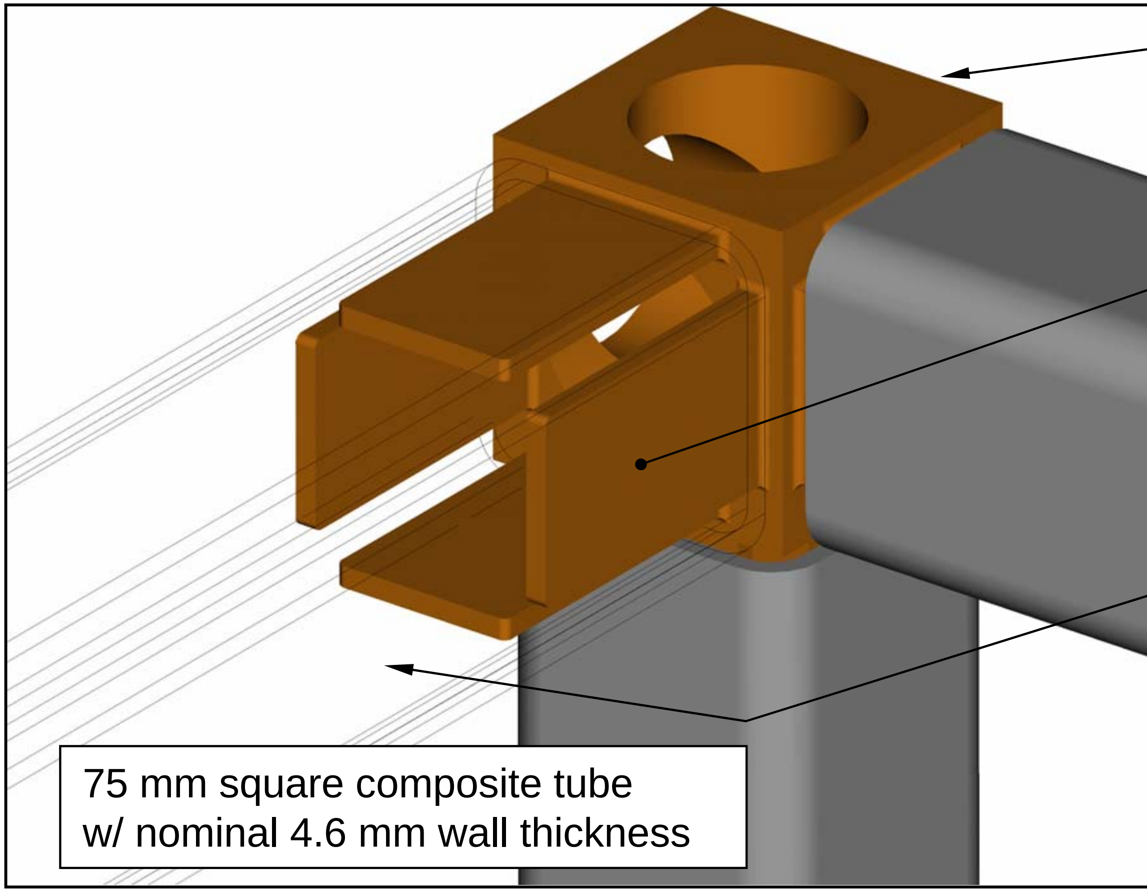
- Design Requirements
  - Metal/composite bonded joints required at a number of nodal locations on the JWST/ISIM composite truss structure to accommodate bolted instrument interfaces and flexures.
  - Survival temperature at 22K (~ – 400^{o}F); – 271K total ΔT from RT.
  - Composite truss tube with high axial stiffness (~23 msi) and low axial CTE (~ 0 ppm/K).
  - Multiple thermal cycles throughout design life of structure. In order to survive launch loads, joints cannot degrade more than an acceptable amount.

- Design/Analysis Challenges
  - Large thermal mismatch stresses between metal fitting and composite tube at cryogenic temperature (22K).
  - Analysis and design experience is very limited for metal/composite bonded joints at temperatures below liquid nitrogen (~80K).
  - Thermo-elastic material properties and strengths for composites and adhesives at 22K are not available and difficult to test for.

ISIM Basic Joint Assemblies



Basic Plug Joint Details



Metal Fitting (Invar 36)

E = 18.8 msi

α = +1.5 ppm/K

Adhesive Bond (EA9309)

E = 1.1 msi

G = 0.4 msi

α = 47.8 ppm/K

Fsu = 11.6 ksi (80 MPa)

Hybrid Composite Tube

E_{axial} = 23 msi

E_{hoop} = 6.7 msi

α_{axial} = -0.13 ppm/K

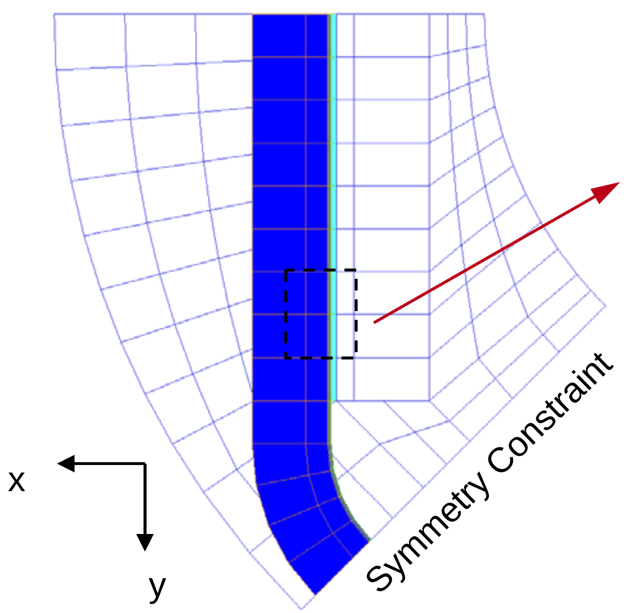
α_{hoop} = +3.7 ppm/K

$\left.\begin{array}{l} S_{zz} = 2.9 \text{ ksi (20 MPa)} \\ S_{zx} = S_{yz} = 5.8 \text{ ksi (40 MPa)} \end{array}\right\}$ interlaminar strengths

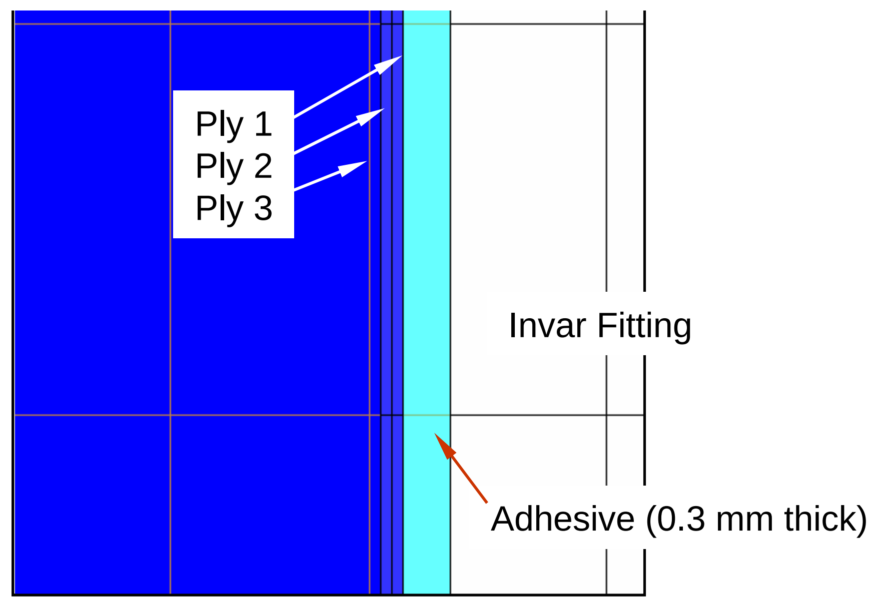
- Stiffness and strength properties are given for 22K.
- Thermal expansion properties are secant CTE from RT to 22K.

Composite Modeling and Mesh Size

- Mesh size: 2.5 mm square in-plane
- Surface plies at bonded interfaces modeled individually
- Aspect ratio ≅ 2.5/0.071 ≅ 35
- Laminate core modeled with thicker elements
- Adhesive modeled with one element through the thickness
- Same mesh size used in all joint FEMs including development test FEMs
- Stress recovery: Element centroid for interlaminar, corner for others

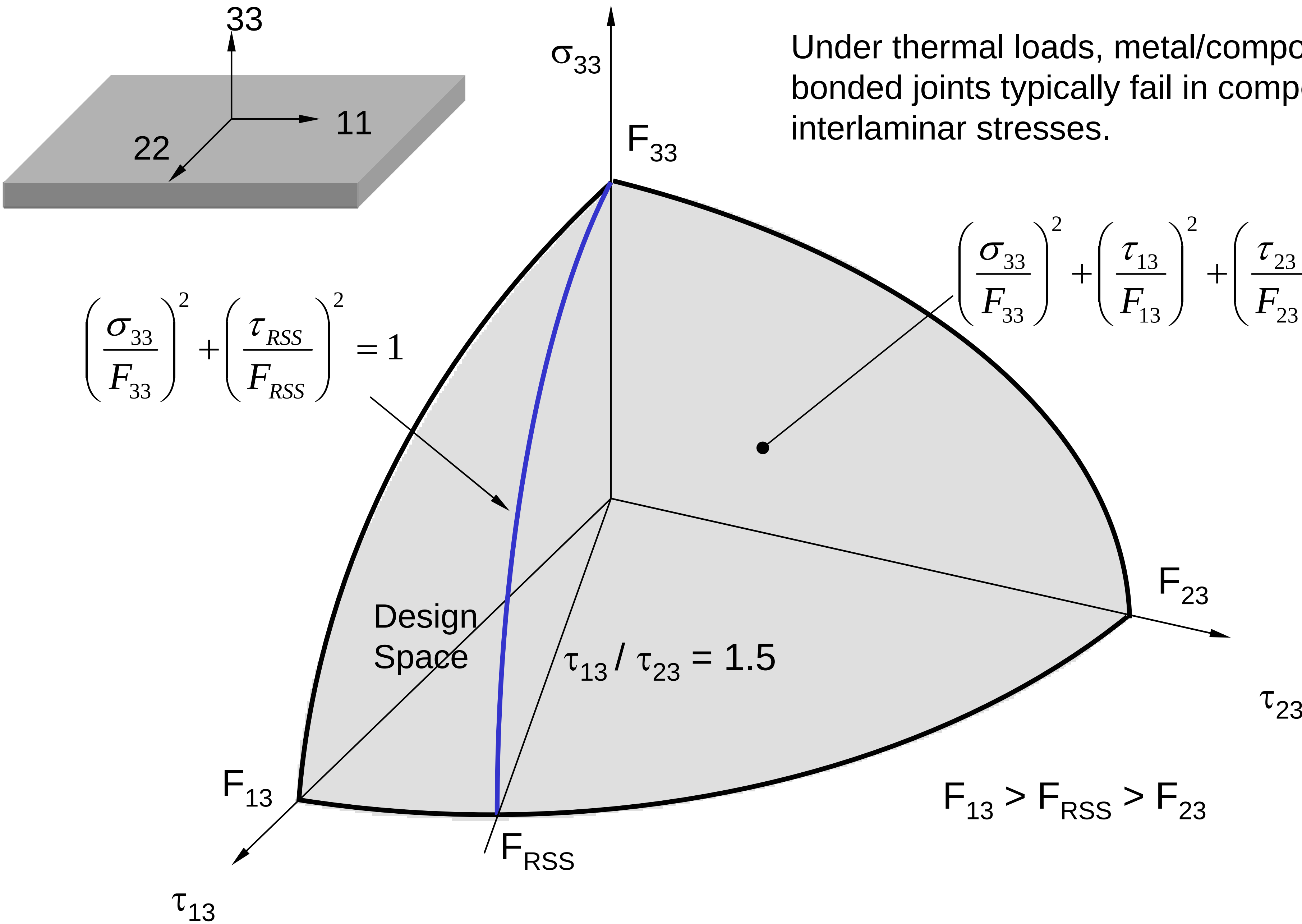


View A-A



Ply 1 – Explicit Props (T300/954-6 Uni Ply)
Ply 2 – Tube Smeared Props (T300/954-6 Uni Ply)
Ply 3 – Tube Smeared Props (M55J/954-6 Uni Ply)

Lamina Failure Criteria – Bonded Joints



Under thermal loads, metal/composite bonded joints typically fail in composite interlaminar stresses.

$$\left(\frac{\sigma_{33}}{F_{33}}\right)^2 + \left(\frac{\tau_{RSS}}{F_{RSS}}\right)^2 = 1$$

$$\left(\frac{\sigma_{33}}{F_{33}}\right)^2 + \left(\frac{\tau_{13}}{F_{13}}\right)^2 + \left(\frac{\tau_{23}}{F_{23}}\right)^2 = 1$$

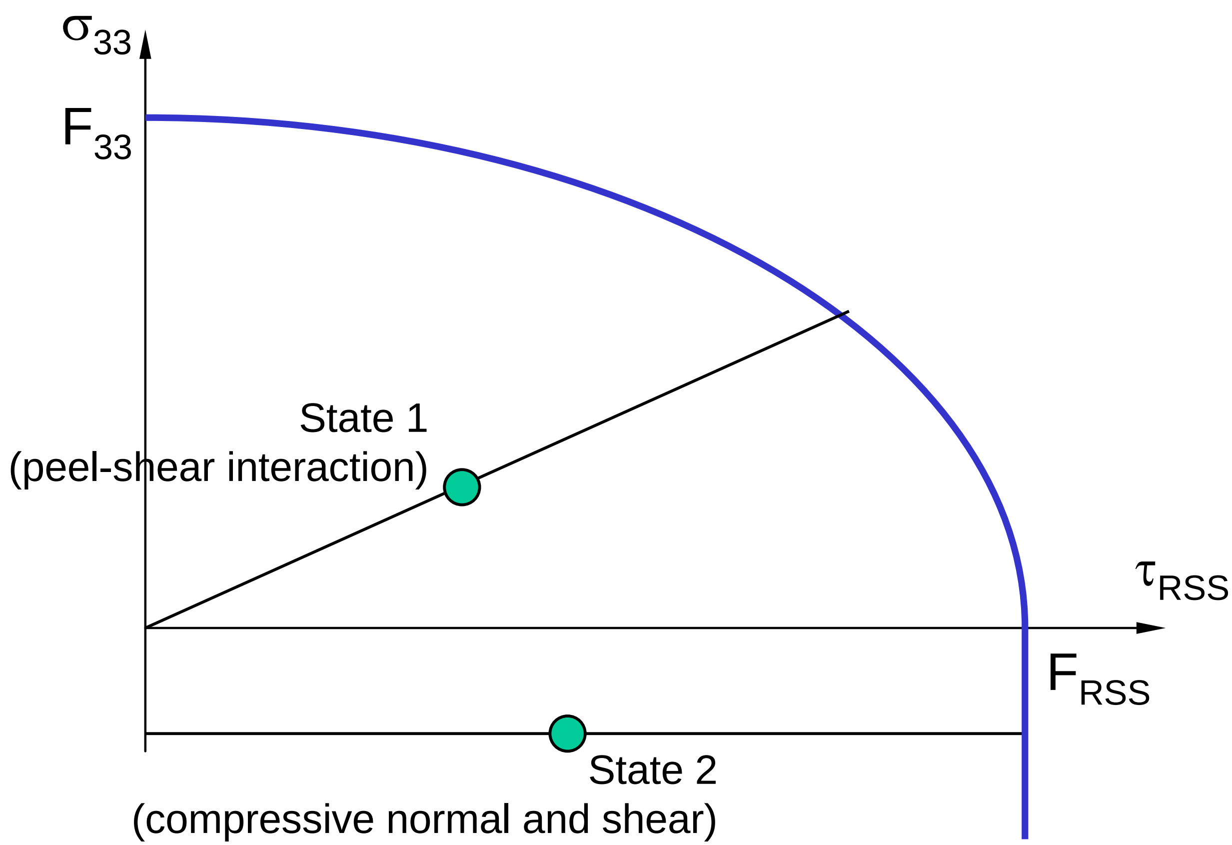
$F_{13} > F_{RSS} > F_{23}$

Interlaminar Failure Prediction

An empirical Interlaminar Failure Criterion is used for critical lamina:

$$\left(\frac{\sigma_{33}}{F_{33}}\right)^2 + \left(\frac{\tau_{RSS}}{F_{RSS}}\right)^2 = 1$$

where σ_{33} is peel stress, τ_{rss} is resultant transverse shear stress, and F terms are material constants dependent on interlaminar strengths, which are being determined by testing.



Margin Calculations

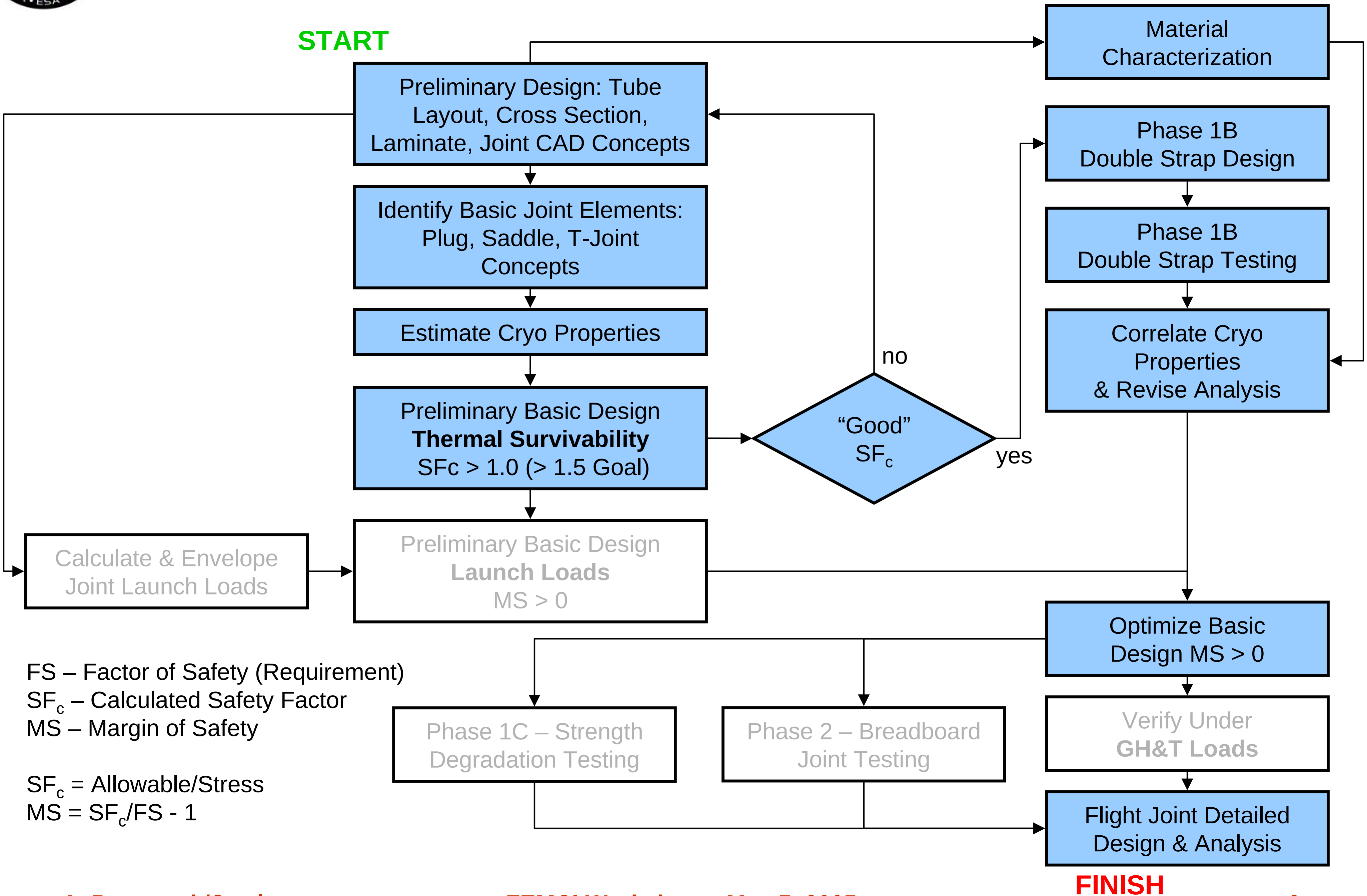
Stress State 1

$$\boxed{MS = \frac{1}{FS \cdot \sqrt{\left(\frac{\sigma_{33}}{F_{33}}\right)^2 + \left(\frac{\tau_{RSS}}{F_{RSS}}\right)^2}} - 1}$$

Stress State 2

$$\boxed{MS = \frac{F_{RSS}}{FS \cdot \tau_{RSS}} - 1}$$

Bonded Joint Design & Sizing Flow

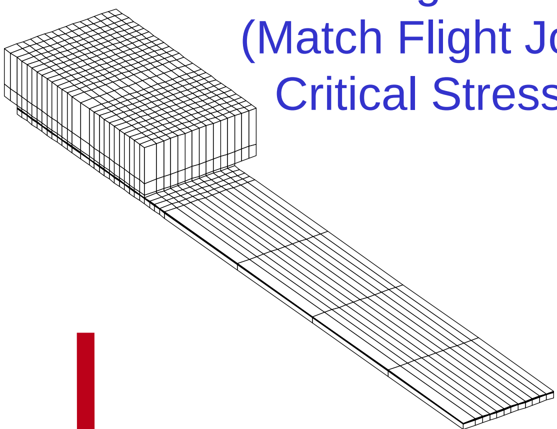


FS – Factor of Safety (Requirement)
SF_c – Calculated Safety Factor
MS – Margin of Safety

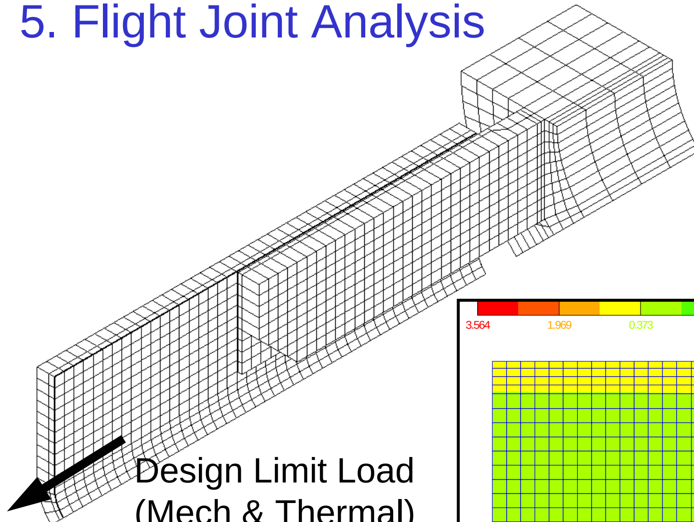
SF_c = Allowable/Stress
MS = SF_c/FS - 1

Bonded Joint Analysis Correlation - Procedure

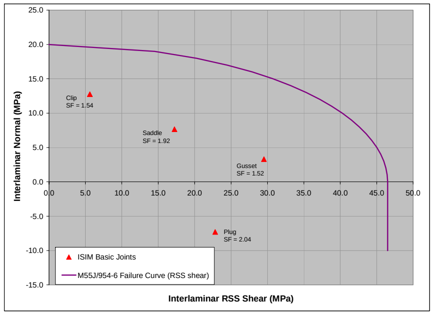
1. Coupon Analysis & Design (Match Flight Joint Critical Stresses)

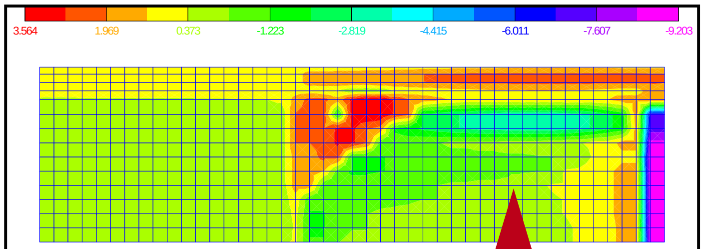


5. Flight Joint Analysis

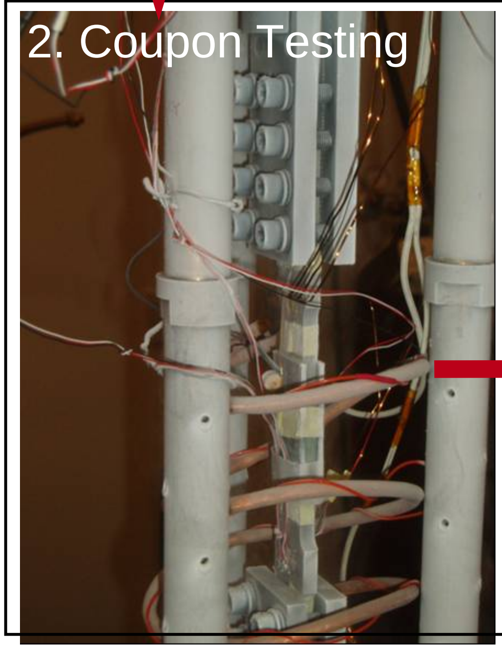


Design Limit Load
(Mech & Thermal)

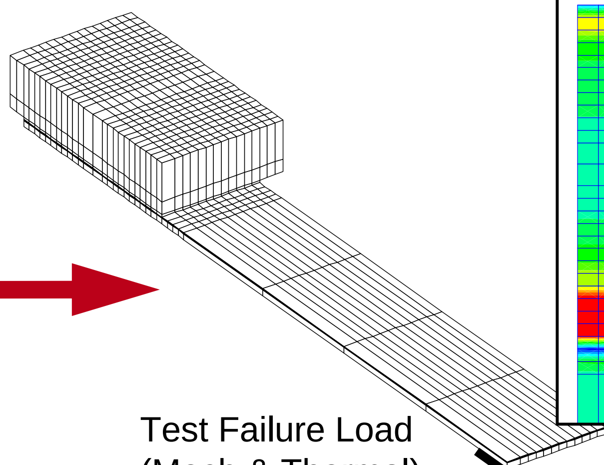




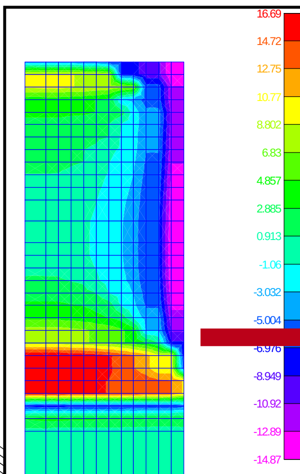
2. Coupon Testing



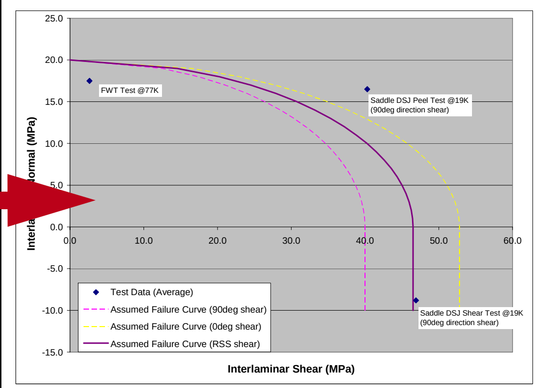
3. Test Coupon Analysis



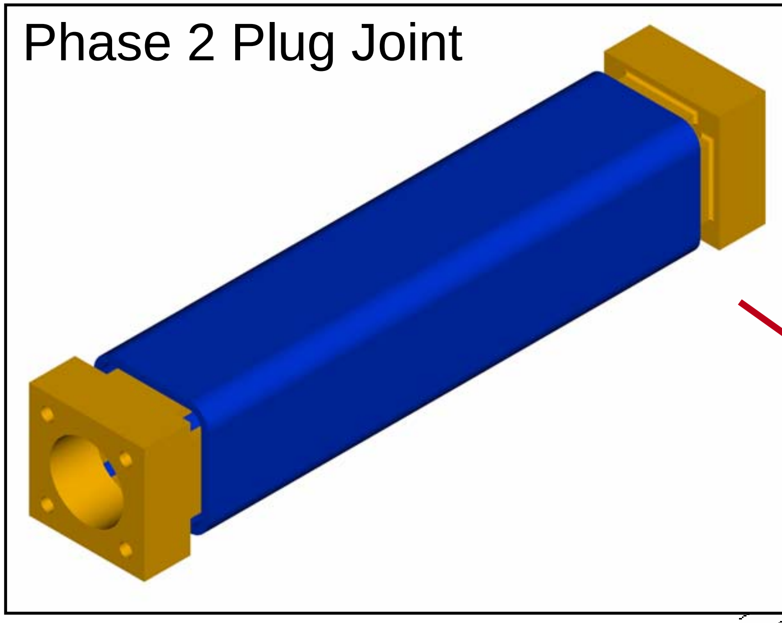
Test Failure Load
(Mech & Thermal)

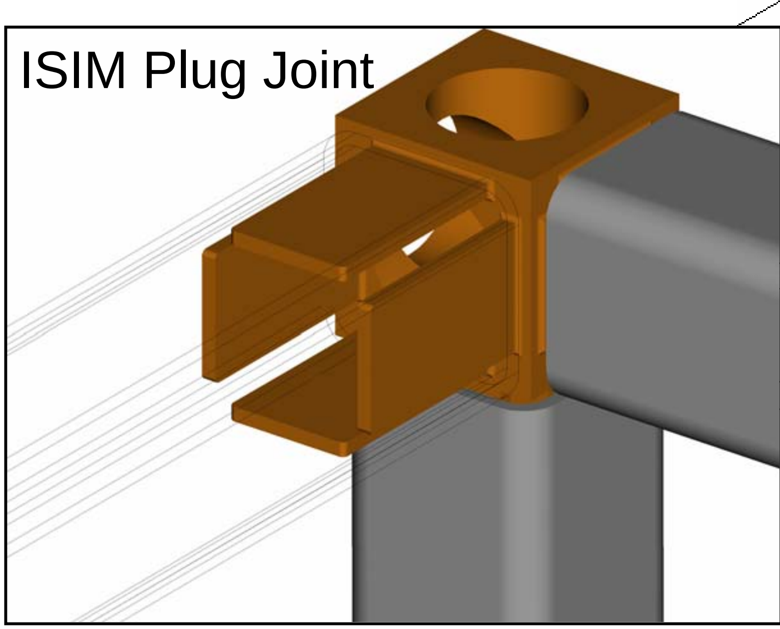


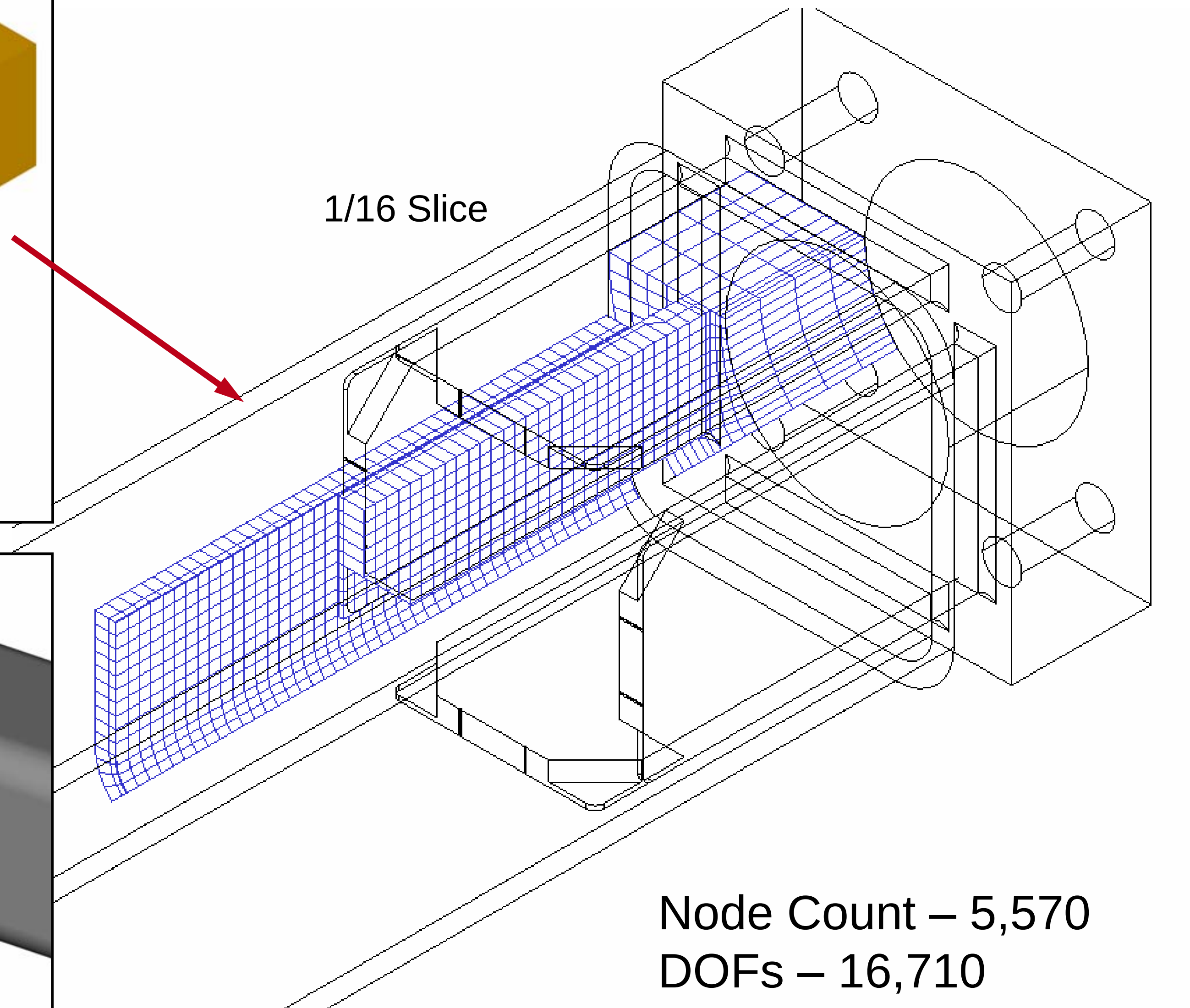
4. Failure Curve



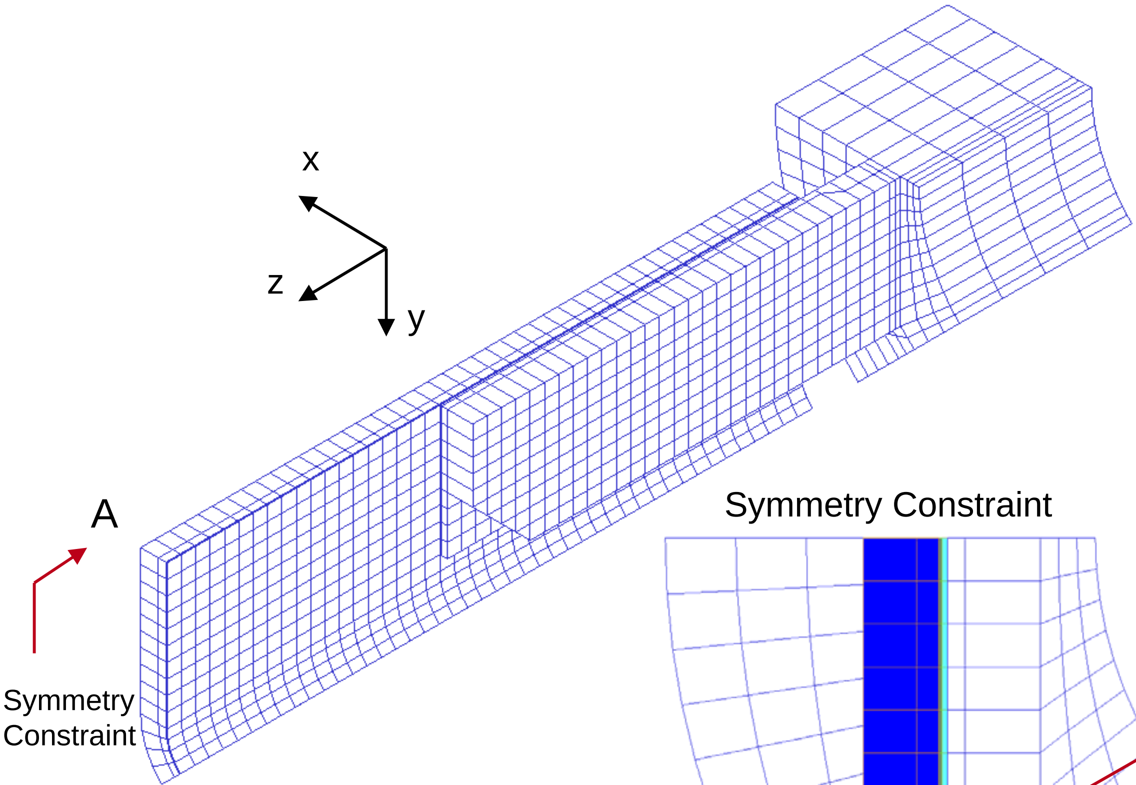
Basic Plug Joint Detailed Stress Analysis

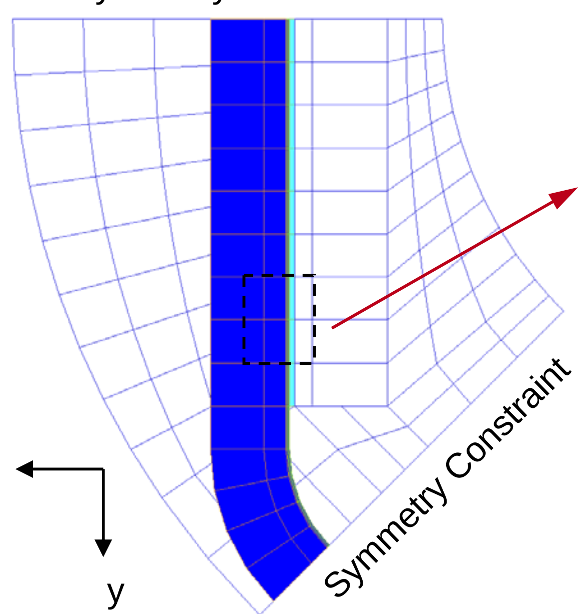




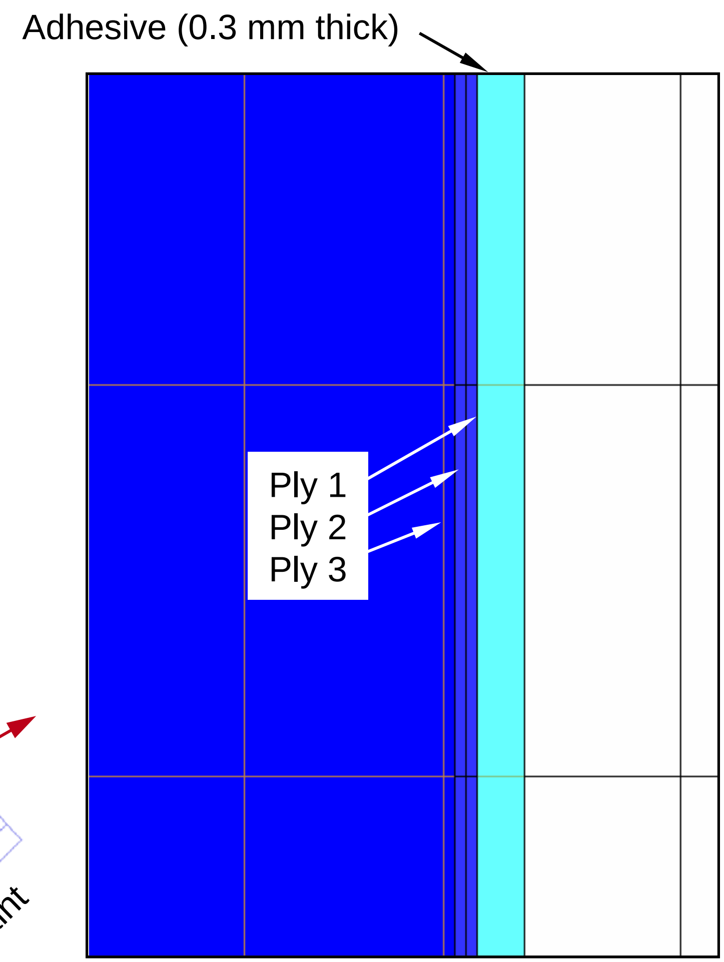


Basic Plug Joint - FEM





View A-A



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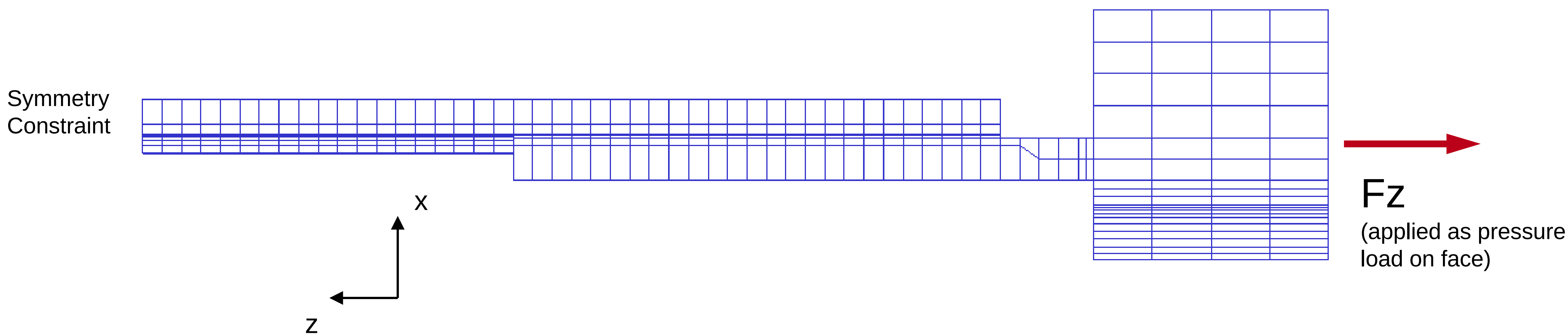
Basic Plug Joint - Applied Loads

Load Case	Type	∆ T (K)	Fz (N)	Remarks
1	Thermal	-271	0	RT to cold survival temperature (22K)
2	Thermal & I/F & 1g	-271	4513	Thermal plus worst case tension (I/F & 1g) and worst case compression (I/F & 1g)
3	Thermal & I/F & 1g	-271	-9096	
4	Launch	0	83200	Absolute max axial load from ISIM beam element model loads run (includes additional effective axial load due to moment load)



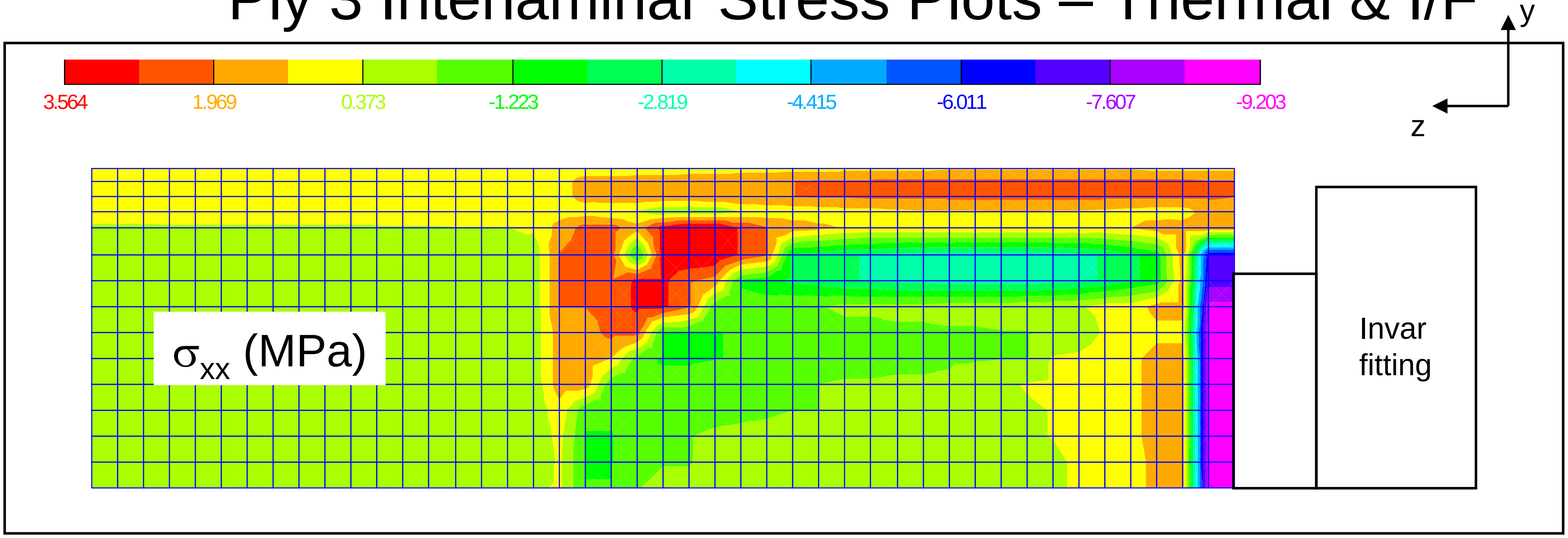
Basic Plug Joint - Margin Summary

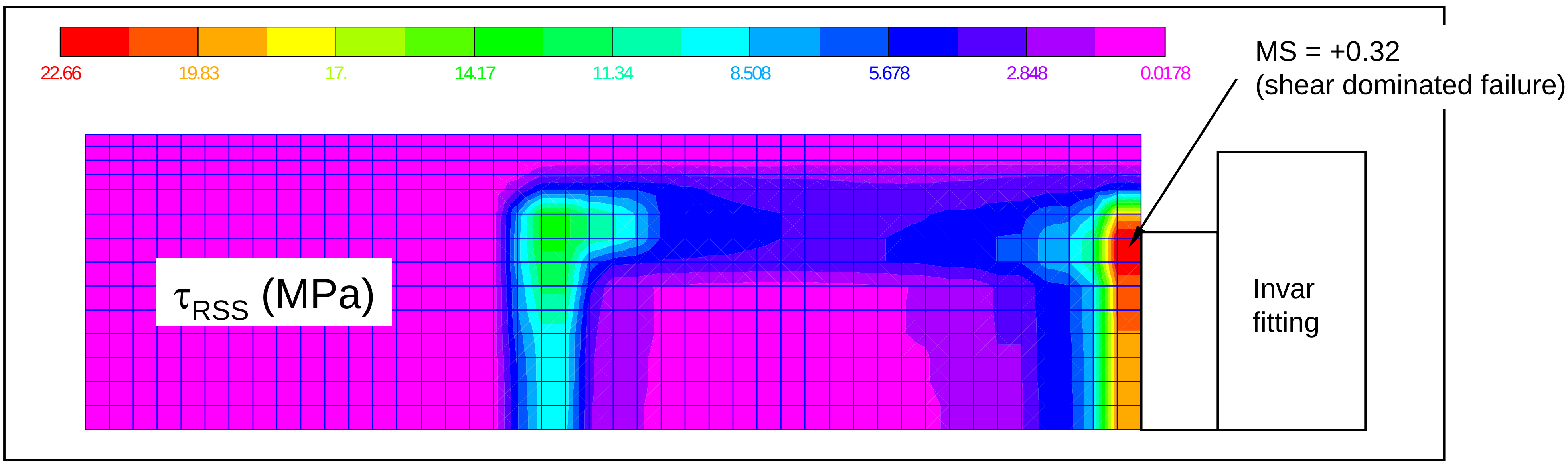
Load Case	Failure Mode		Allowable (MPa)	Abs Max (MPa)	MS	Comments
Thermal & Mechanical (-271K + I/F + 1g)	Ply-1 (T300)	σ-τ interlaminar			+ 0.40	
	Ply-3 (M55J)	σ-τ interlaminar			**+ 0.32**	
	Invar (Blade)	VM yield	275	115	+ 0.91	assume strength properties at cryo to equal properties at room temperature
		VM ultimate	414	115	+ 1.57	
Launch	Ply-1 (T300)	σ-τ interlaminar			+ 0.92	
		s11	1380	162	+ 3.73	max corner stress. allowables are based on explicit props.
		s22	81	12.4	+ 2.63	
	Ply-3 (M55J)	σ-τ interlaminar			**+ 0.38**	
	Tube	s11	439	157	+ 0.55	max corner stress. allowables are based on tube smeared props.
		s22	241	42	+ 2.19	
	Invar (Blade)	VM yield	275	167	+ 0.32	max corner stress in blade, localize stress raisers at blade/hub interface not included
		VM ultimate	414	167	+ 0.77	

- Margins presented at PDR, Jan 2005.

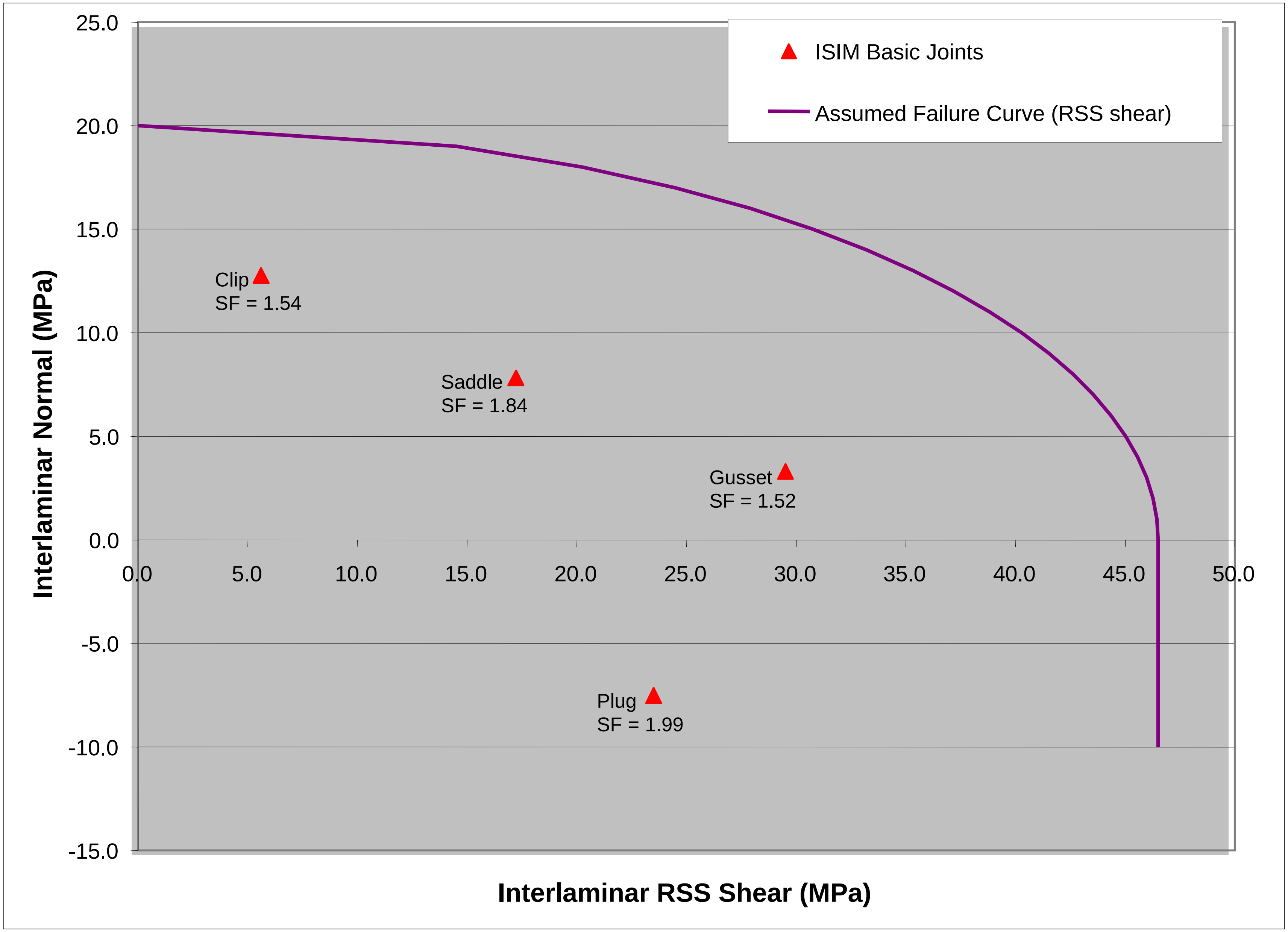
Basic Plug Joint

Ply 3 Interlaminar Stress Plots – Thermal & I/F

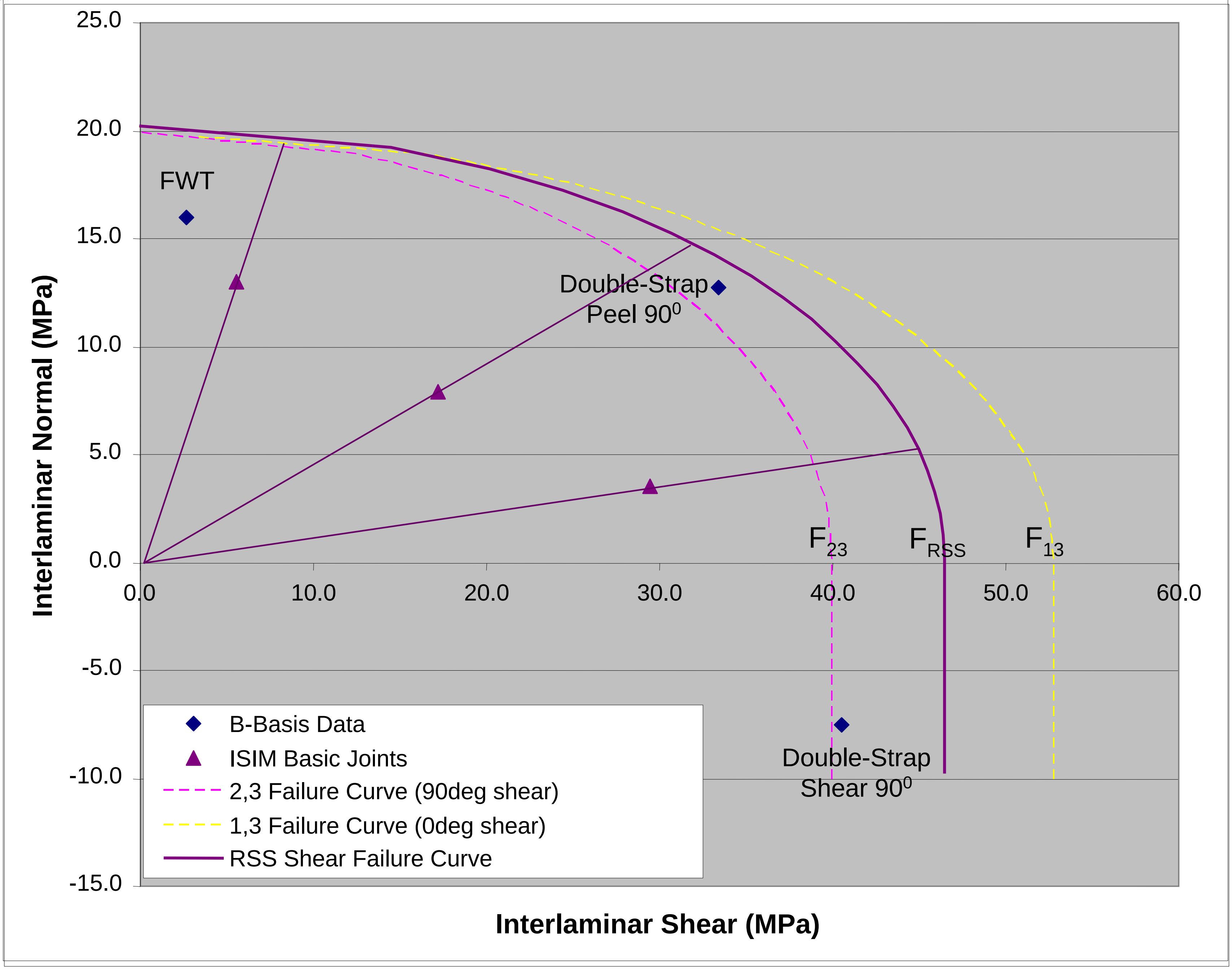




SF and Failure Curve – Basic Joint Assemblies



DSJ Test Data and Estimated Failure Curve



Remarks and Conclusions

- Material characterization testing and joint development testing are in progress. Test results will be critical for analysis correlation and the final design/analysis of the ISIM metal/composite bonded joints.
- A Phase-2 test program is underway and will include thermal survivability testing of basic joints including a plug joint.
- An evaluation of strength degradation due to multiple thermal cycles will also be included in the joint development test program.
- The ISIM Structure successfully passed PDR (Preliminary Design Review) in January 2005, design requirements have been met. Critical Design Review is scheduled for December 2005.